EXPLORING LONG-TERM VARIABILITY IN ACTIVE GALACTIC NUCLEI VIA MONTE CARLO SIMULATIONS OF OPTICAL SPECTRA

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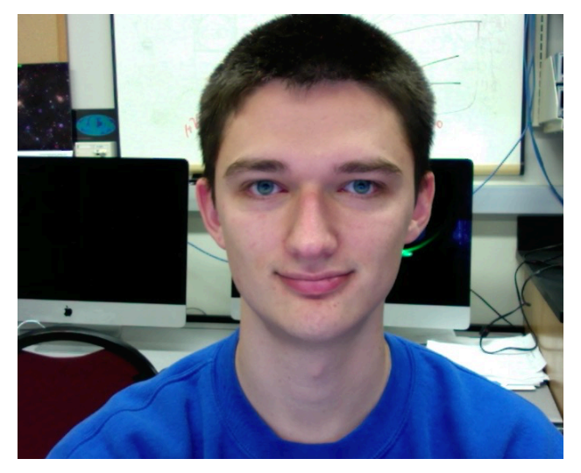
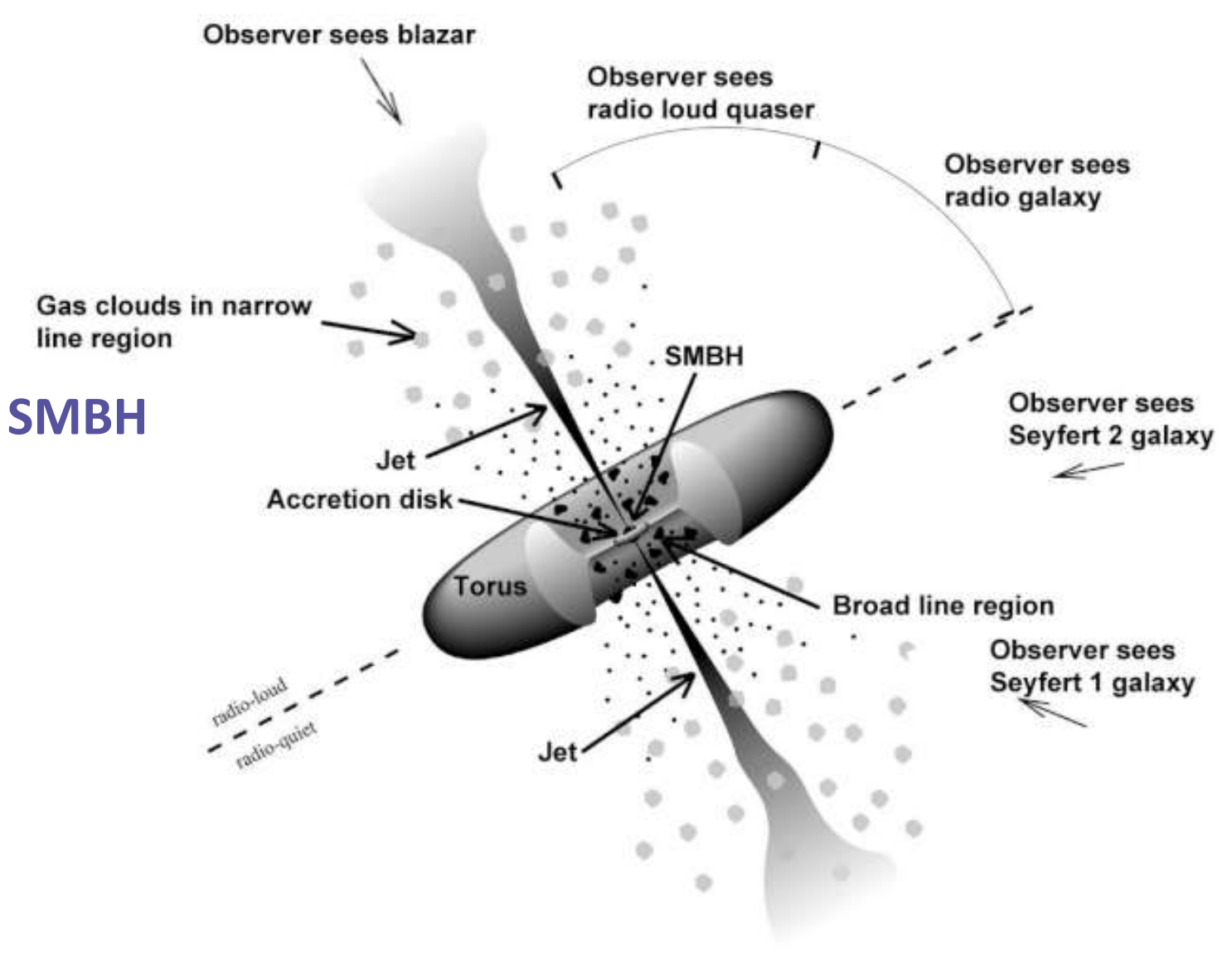


ABSTRACT

The emission produced by accretion of matter onto supermassive black holes in Active Galactic Nuclei (AGNs) dominates the overall emission of the universe over almost all of the electromagnetic spectrum. Continuum and emission-line variability of AGN provides a powerful probe of the various time scale structures in the central regions of these sources. By investigating the properties of variability in these sources, we hope to identify the physical processes driving AGN, their environments, and even provide crucial constraints on their detection rates, and thus to their true census. Prompted by recent evidence for decade-scale variability in a small sample of nearby AGNs, and the general lack of data that would sample such a phenomenon, we are exploring the long-term variability in the optical nebular line emitting gas in galaxy centers via Monte Carlo simulations. **Based on observational constraints of a large variety of parameters that characterize the optical spectra of nearby AGN, we build a sample of a million objects, apply and test various variability patterns, and then evaluate the parameter space that determine the detection threshold of their signature as accreting systems (e.g., emission lines that are Doppler broadened to thousands of km/s).** This investigation adds a novel and powerful dimension to AGN selection by future surveys, with direct consequences for better understanding of their life cycle, their spatial density, and ultimately for the role played by AGN in galaxy formation and evolution processes.

Active Galactic Nuclei: Main Components and Emission

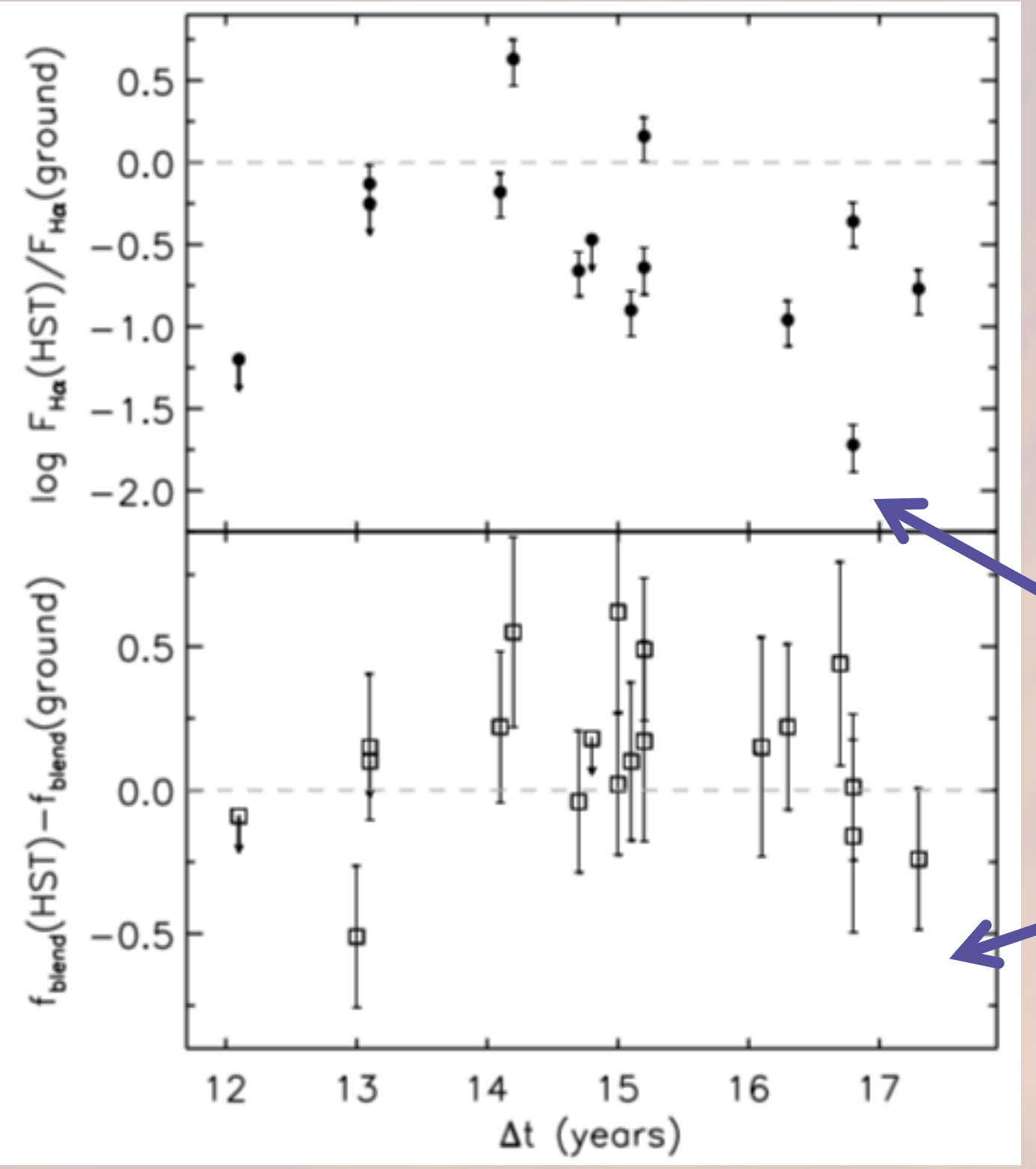
AGNs are galaxy centers of tremendous luminosities whose radiation originates from matter swirling around a supermassive black hole with mass between millions to billions of solar masses (e.g., Peterson 1997).



- AGN Main Features:
  - Supermassive (10^7-$10^9 M_{sun}$) black hole (SMBH)
  - Accretion disk
  - **Broad line region (BLR)**
    - **Gas moving at >1000s of km/s → signature for accreting SMBH**
  - Narrow line region (NLR)
    - Gas moving at 100s of km/s
  - Different viewing angle determines observation of different components
  - e.g. edge-on view BLR is obscured by dust in the torus
- BLR is Not Always Detected. Possible Reasons:
  - Naked AGN (no BLR, only narrow emitting clouds)?
  - Obscured by dusty torus (matter of inclination in the plane of the sky)
  - Buried in host galaxy light (BLR too weak relative to surrounding light)
  - **Variability: one epoch observation caught BLR in minimum phase**

AGN Variability & Recent Evidence for Decade-Scale Variation

Periodic variations in observed flux from AGN are a powerful tool for probing the physical phenomenon driving them. By analyzing short-term variations in brightness from these objects, astrophysicists were able to deduce that the size of these objects must be comparable to a solar system and thus accretion of matter onto supermassive black hole must be what powers them.

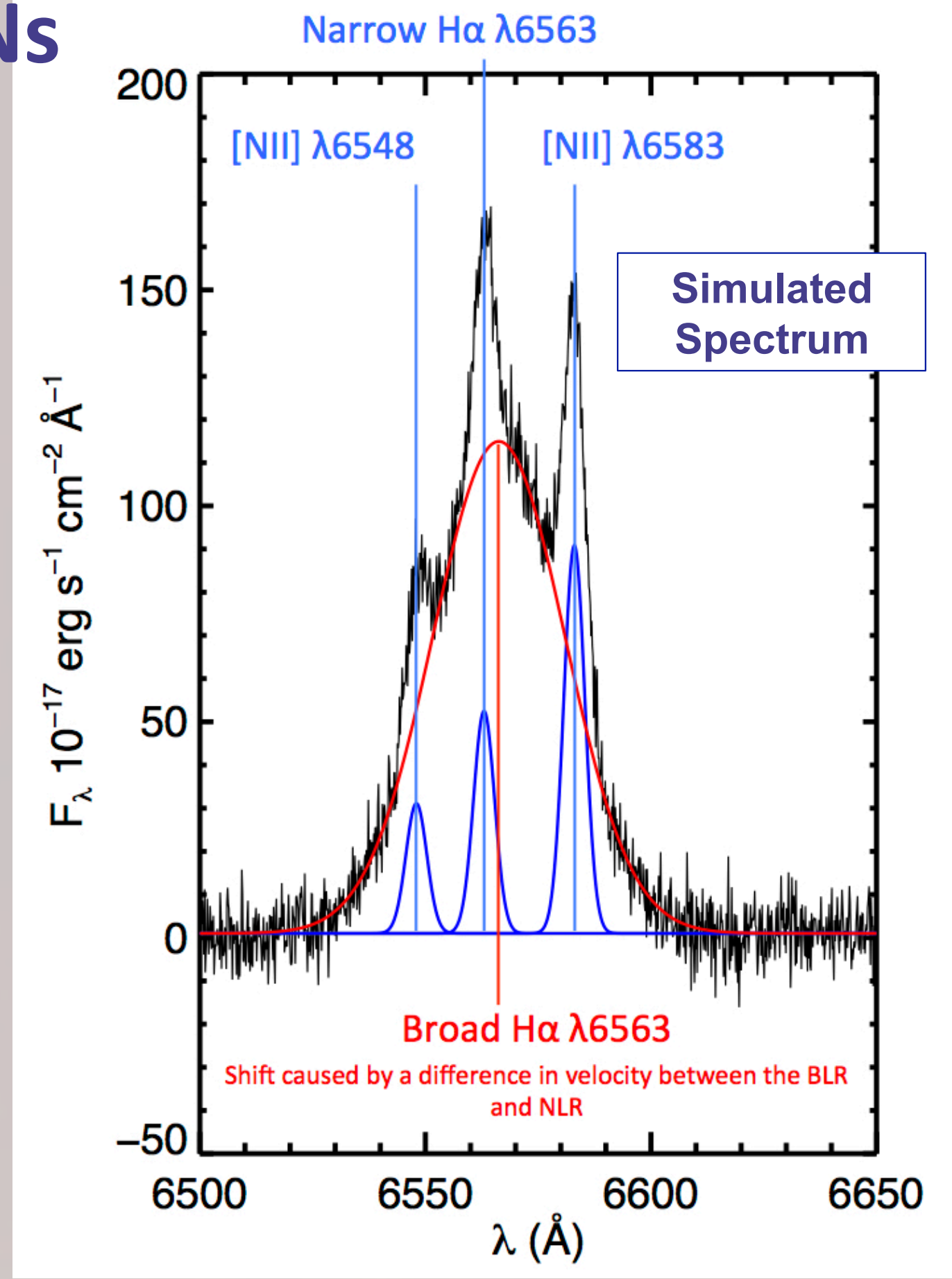


Short-Term Variability (Time-Scales < 1 Year)

- Well studied soon after the discovery of quasars (1963)
- Relatively easy to gather data
- Determine size of BLR through reverberation mapping (e.g., AGN Watch; OSU; Peterson 2001)

- **Long-Term Variability (Time-Scales > 10 Years)**
  - Very little to no research
  - Much more difficult to gather data (requires more time and money)
  - Recent tantalizing evidence Constantin et al. (2015)
    - Galaxies observed 12-17 years apart showed different strengths in broad Hα Fluxes
    - Higher contrast in later observation with Hubble Space Telescope (HST-STIS)
      - ✓ **Easier to detect weaker emission, possibly with lower fluxes in a variability cycle.**
      - ✓ Fraction of Hα flux in the broad component tends to be higher at later observation
  - Understanding and quantifying long-term variability is crucial for constraining the BLR detection rate in one time survey of AGN → Obtain a true census of actively accreting SMBH in the universe.

Simulating a Survey of 10^4 AGNs



Model Design:

- C++ code
- Optical spectra cover λ6500Å – λ6650Å
  - Covers the Hα and [NII] doublet region

Emission lines

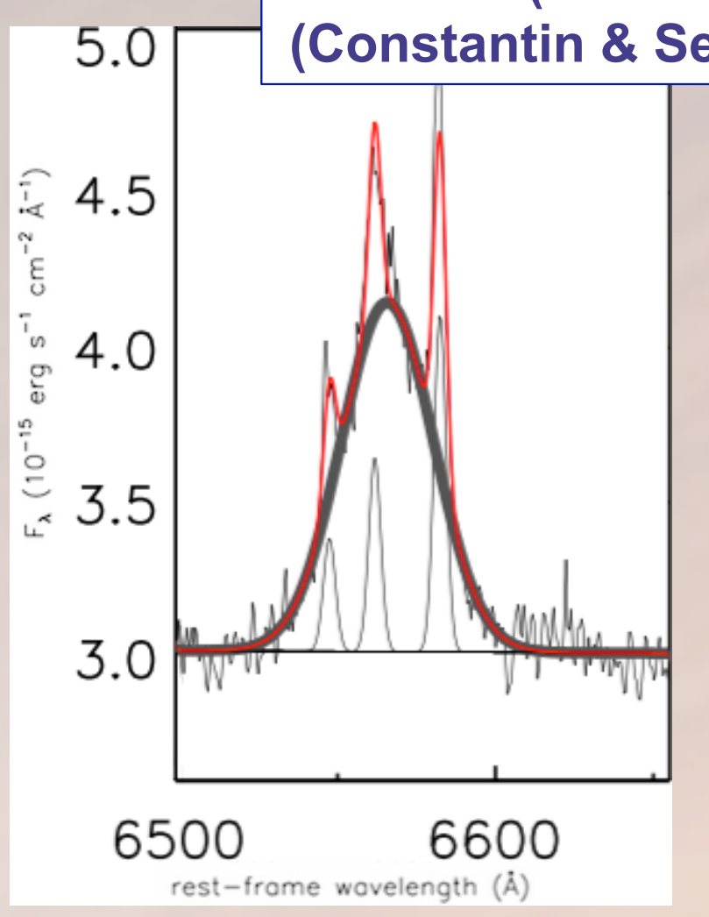
- Modeled as a Gaussian distribution
  - Center
  - FWHM (width of the line in km/s)
  - Total Flux (area under the curve)
- Narrow Hα at 6563Å + Broad Hα
- [NII] doublet (also originating from NLR)
  - [NII]λ6548 is 1/3 flux of [NII]λ6583

Other components

- Continuum
  - Modeled with line: y=1 (subtracted off in real data)
- Noise
  - Modeled with random numbers

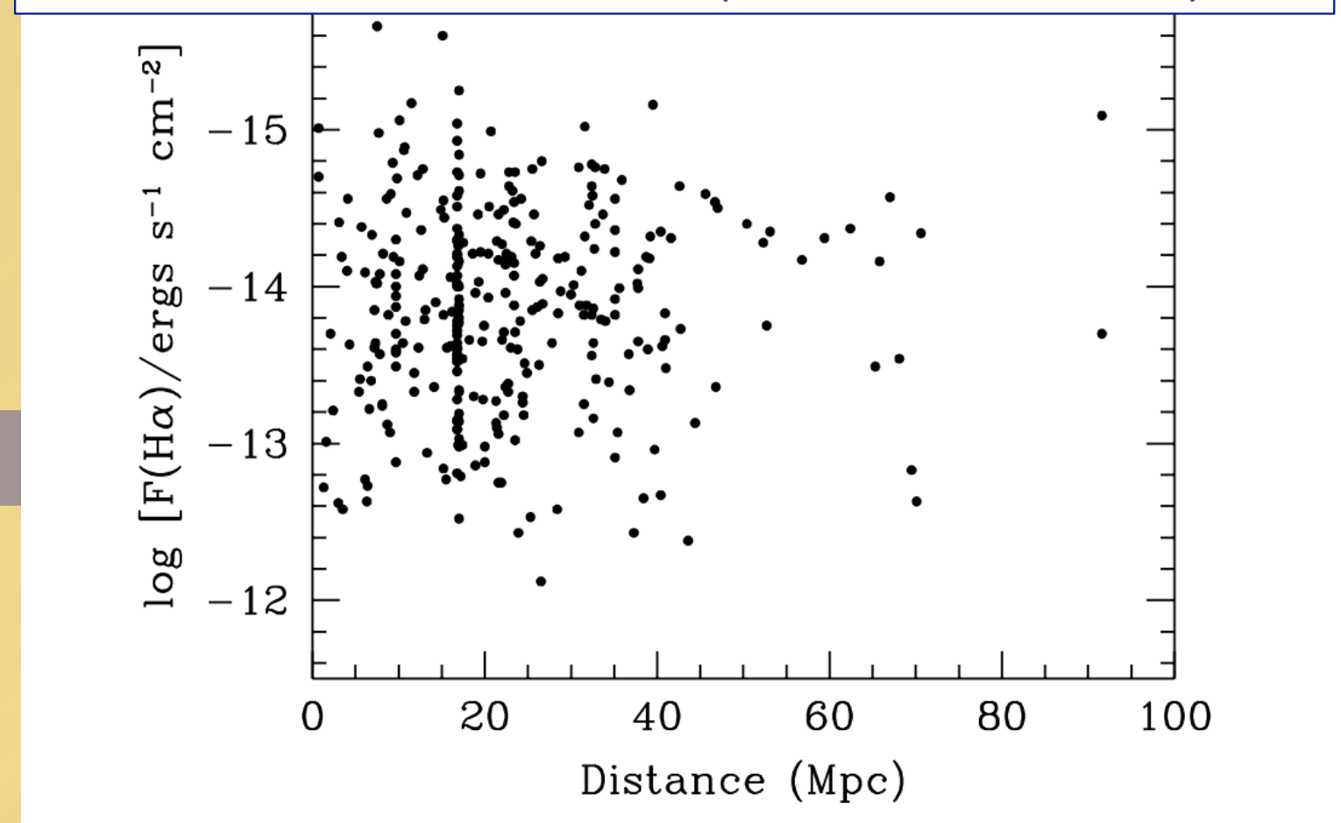
- A set of 7 parameters completely defines a given object's spectrum

Parameter	Minimum	Maximum
$F_{H\alpha\_narrow}$ in erg s^{-1} cm^{-2}	10	100000
[NII]λ6583 / Hα	0.3	5.6
$F_{H\alpha\_broad}$ in erg s^{-1} cm^{-2}	10	100000
FWHM(NLR) in km s^{-1}	100	800
FWHM(BLR; Hα) in km s^{-1}	1000	7000
Δv (broad relative to systemic) in km s^{-1}	-50	1300
Signal-to-noise Ratio	1	20

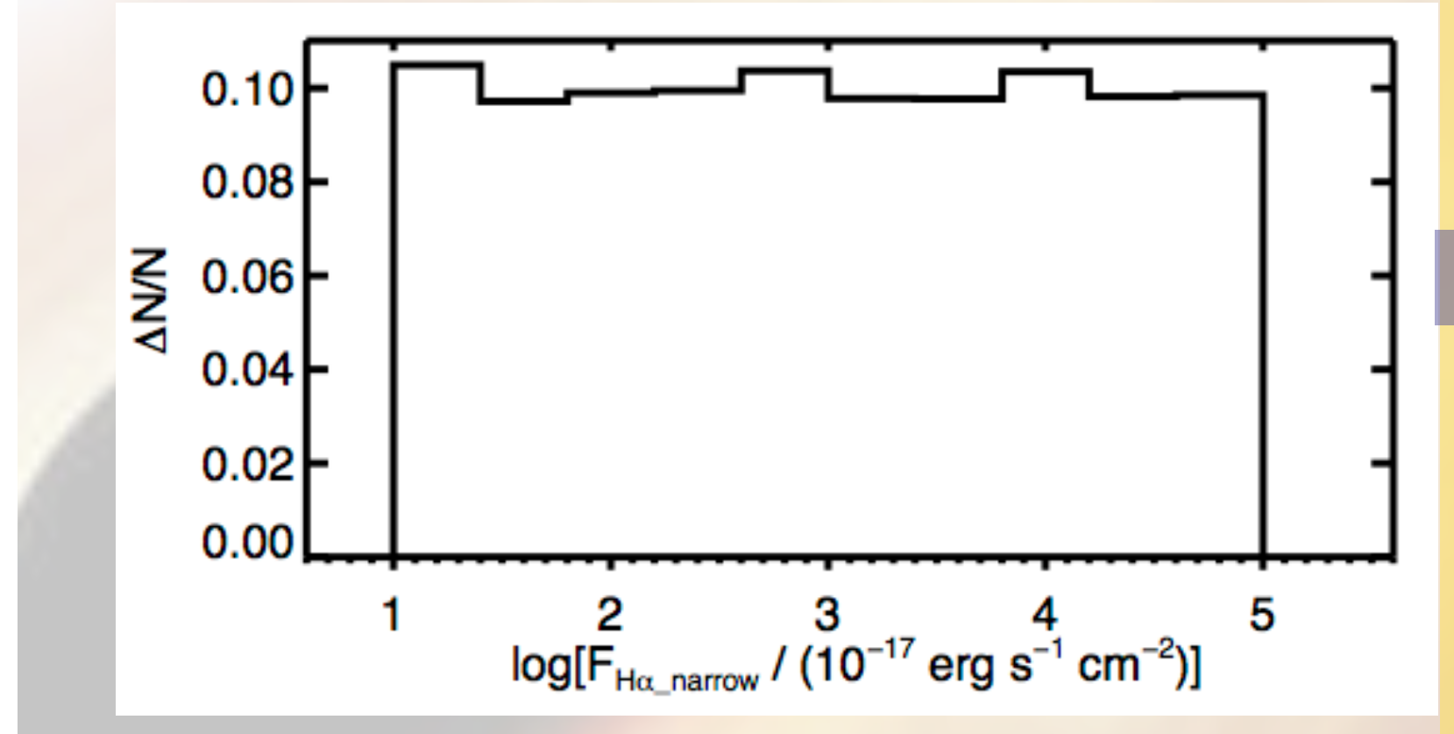

Observed Spectrum: M94 (HST-STIS) (Constantin & Seth 2012)

- (to begin with) All parameters are modeled with uniform distributions via Monte Carlo methods.
- Ranges of parameters are based on results from AGN surveys (Ho et al, 1997a, 1997b, Constantin et al. 2015); e.g., measured and modeled distribution of flux (Hα narrow):

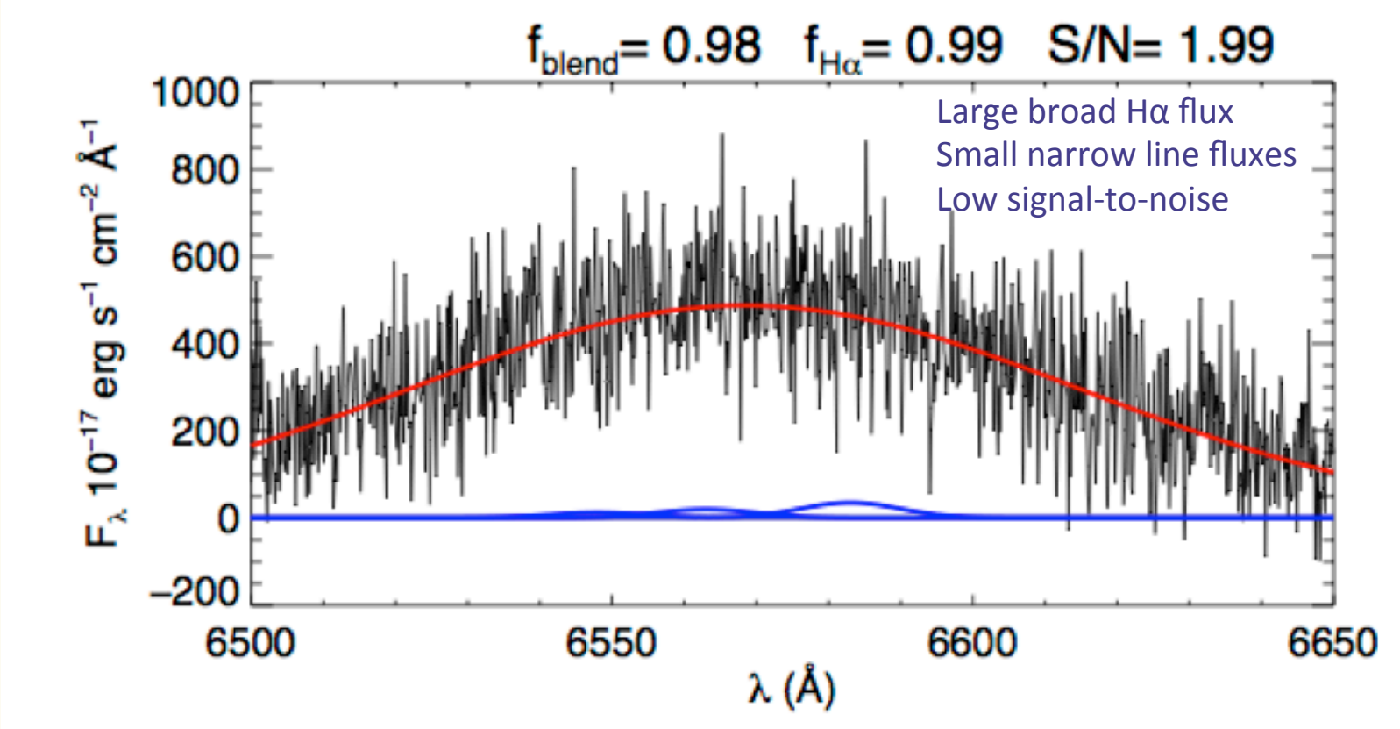
Measured Hα narrow flux (from Ho et al. 1997a)

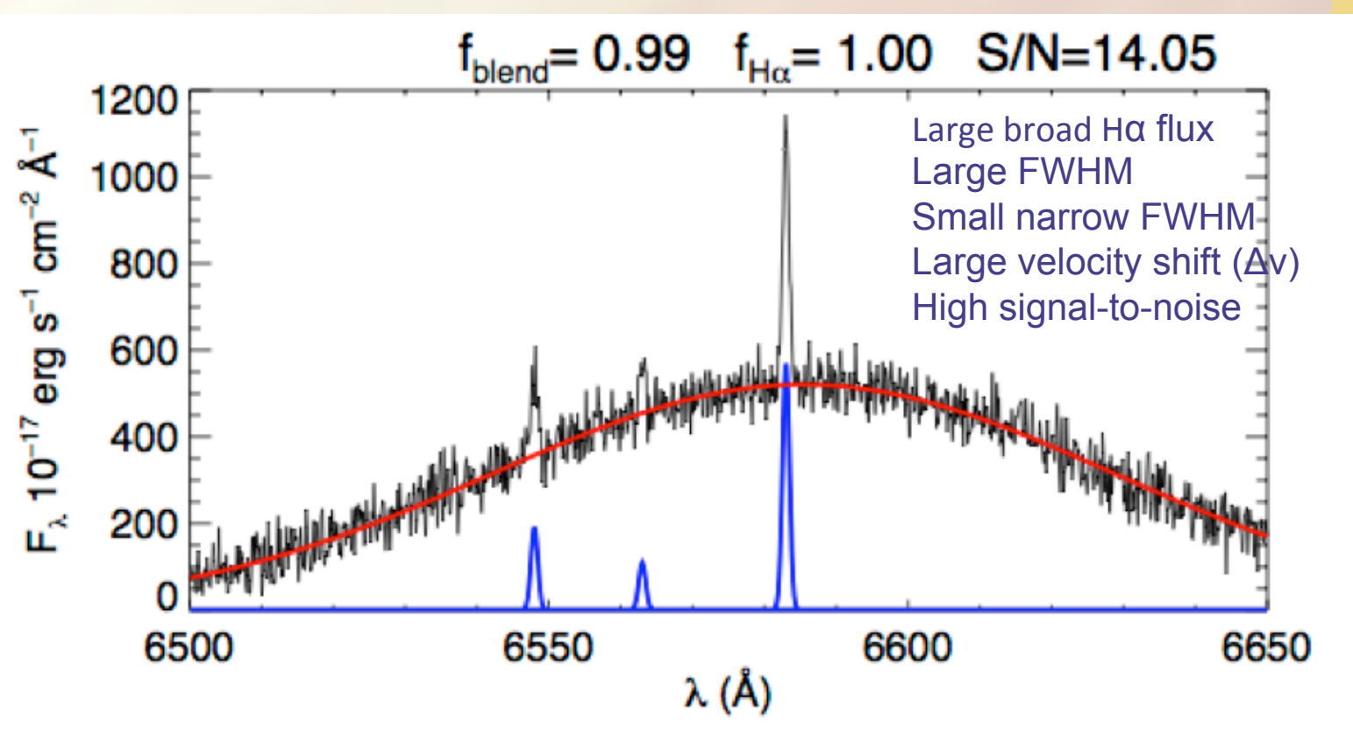


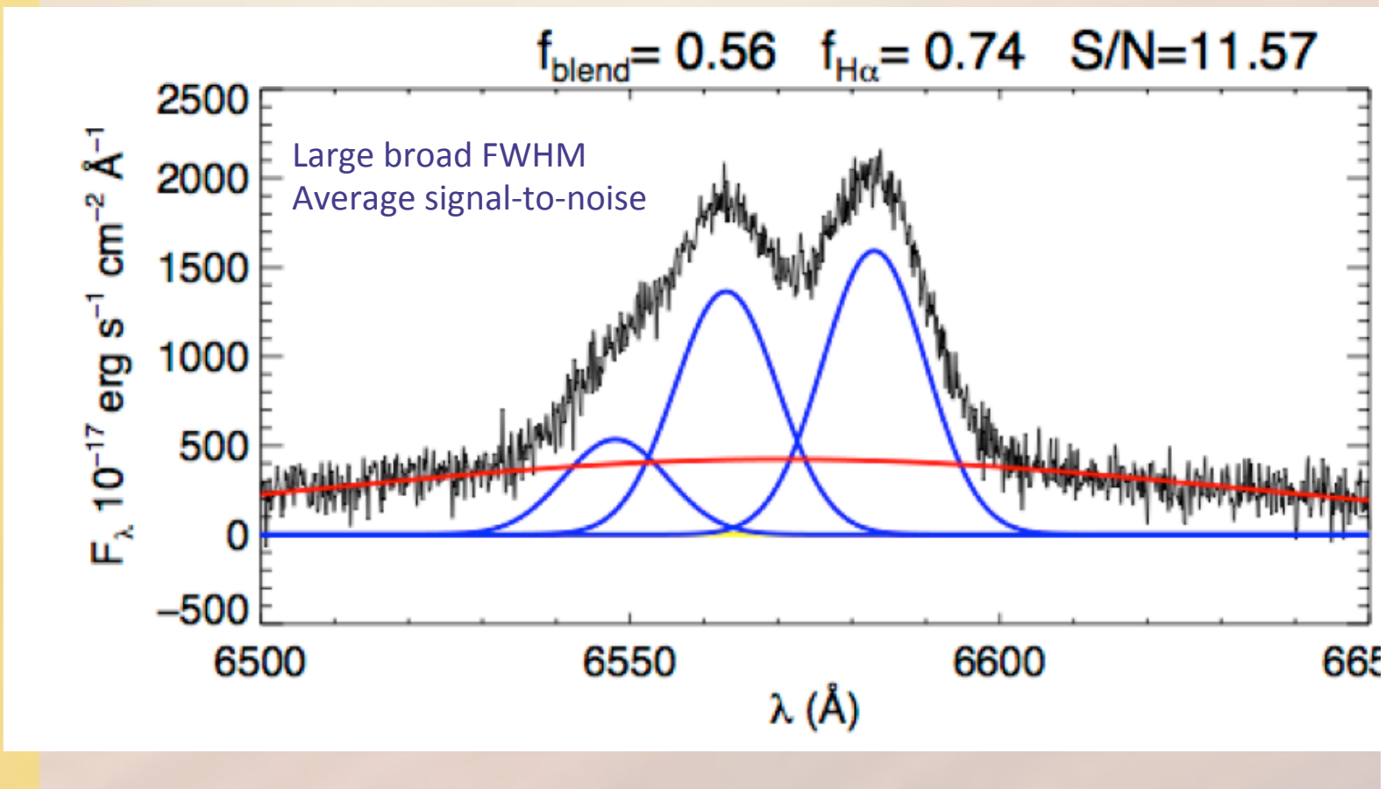
Modeled distribution of Hα narrow flux

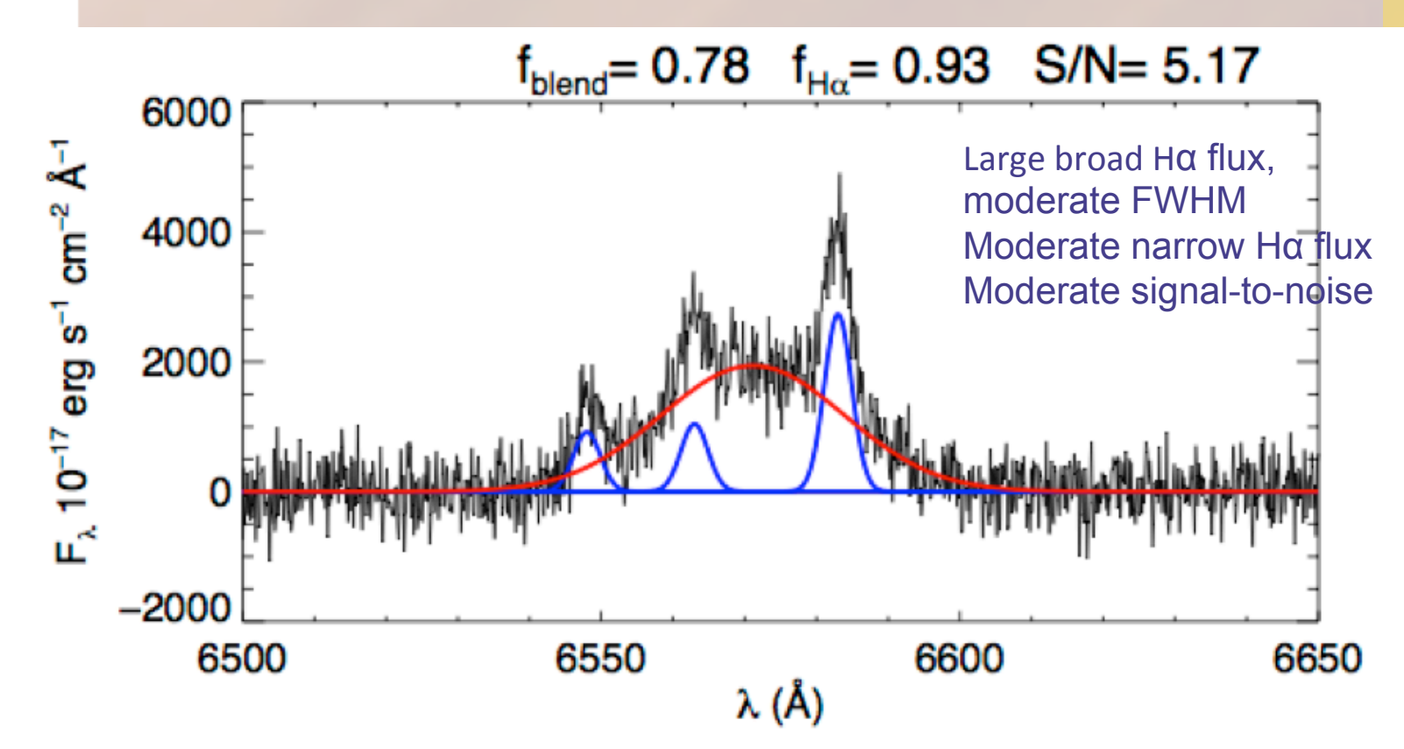


Examples of Simulated Spectra


f_{blend}= 0.98 $f_{H\alpha}$= 0.99 S/N= 1.99


f_{blend}= 0.99 $f_{H\alpha}$= 1.00 S/N=14.05


f_{blend}= 0.56 $f_{H\alpha}$= 0.74 S/N=11.57


f_{blend}= 0.78 $f_{H\alpha}$= 0.93 S/N= 5.17

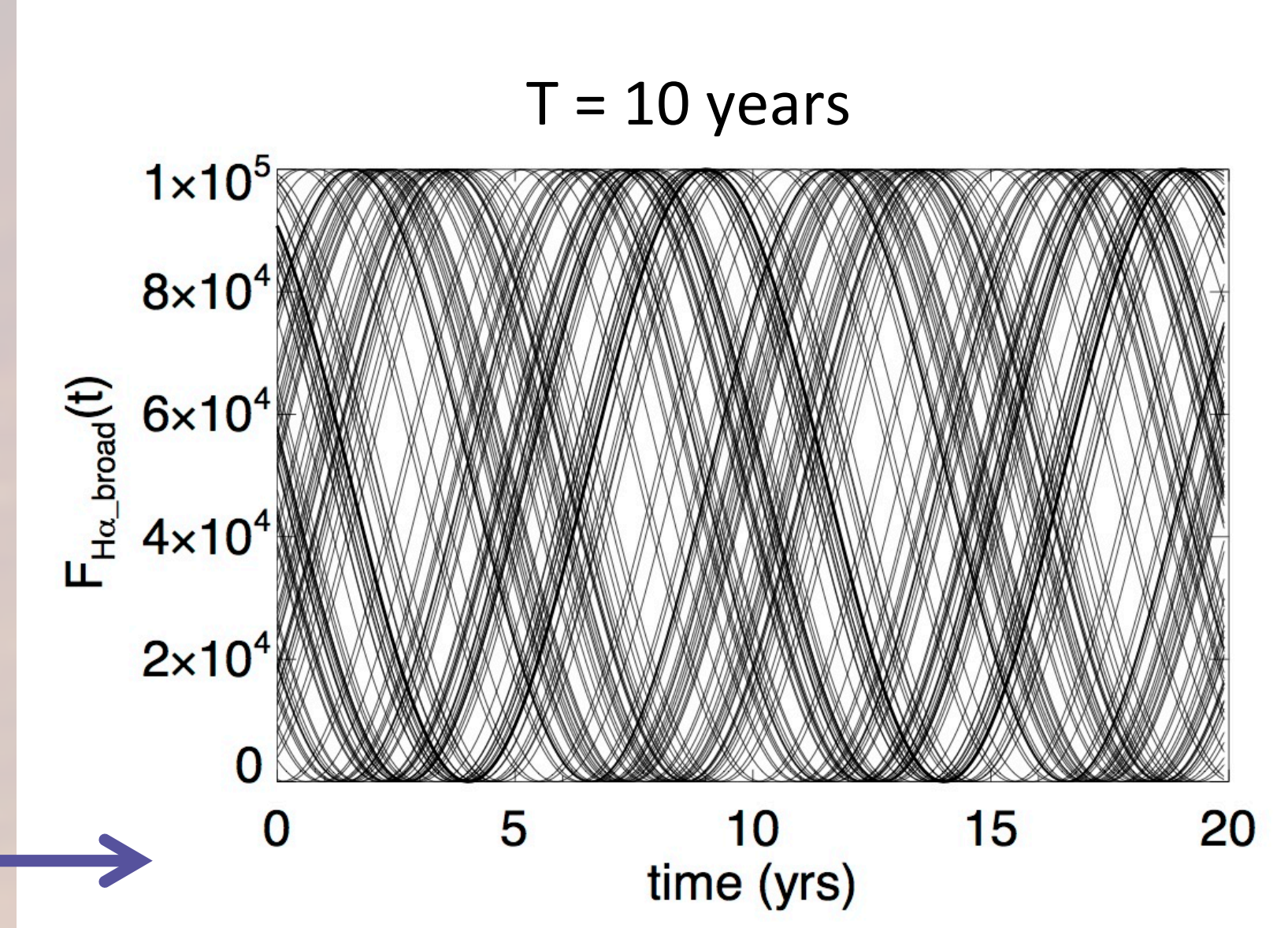
Modeling Variability in the Broad Hα Flux

- Assume simple sinusoidal variation in the flux of the Broad Hα emission.

$$F(t) = A\sin\left(\frac{2\pi}{T}t + \varphi\right) + F_{\min} + A$$

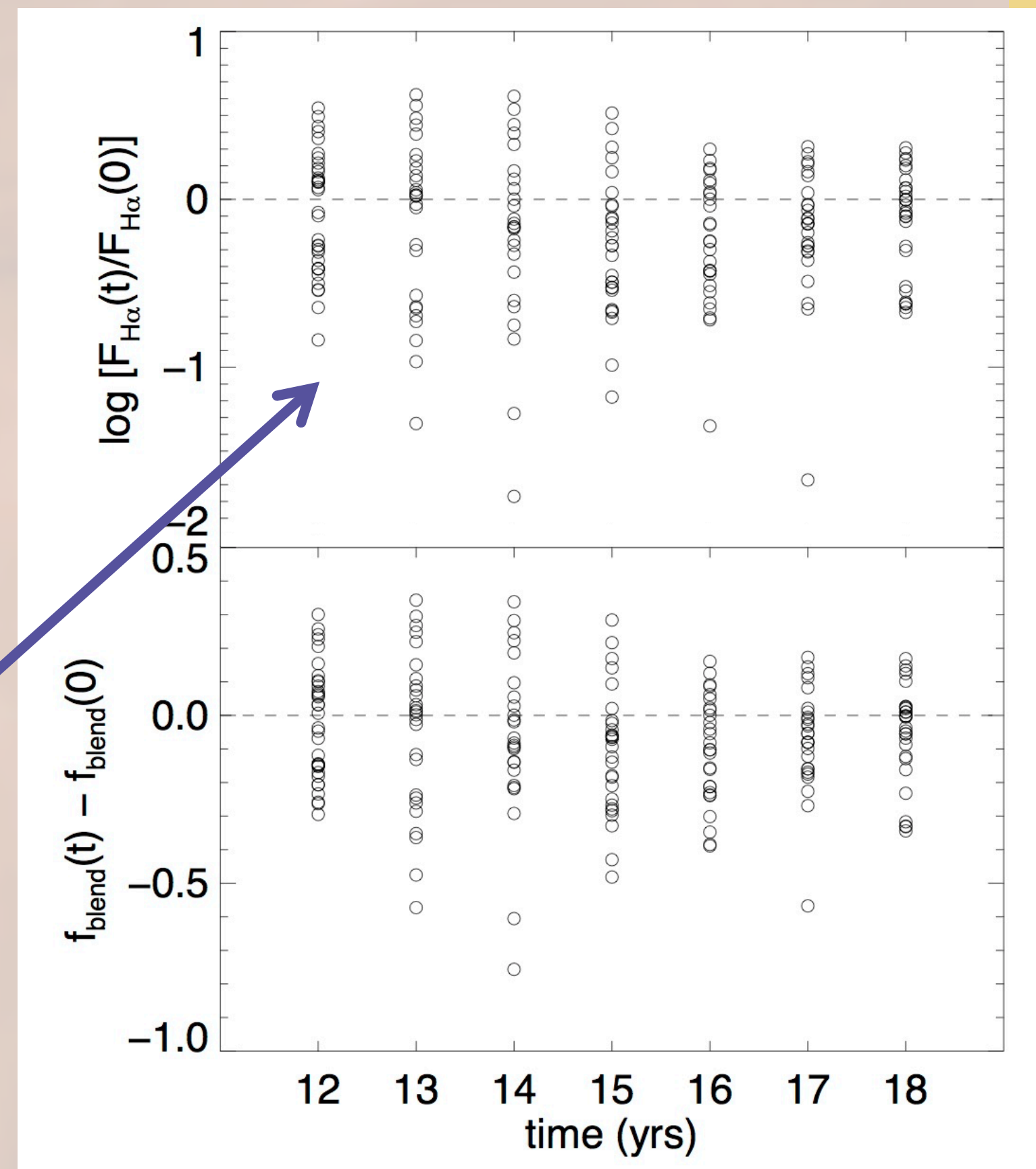
- Constrain the variability parameters:
  - Model/build distribution of initial broad flux (at first observation)
  - Range of broad flux is the range of variation (to match data)
- The amplitude of variability (A) is half the range A = $(F_{max} – F_{min})/2$
- Add term to raise the flux F(t) from being periodic between –A and A to be periodic between F_{min} and F_{max}
- The initial phase (φ) is modeled to match the initial distribution of broad Hα fluxes

- Test period of variation T = 10 years (plot 1% of modeled objects)



- Calculate fraction of flux in broad Hα emission at various times in the variability cycle.
- Record and compare with later "observations" the **broad Hα flux and relative strength to total** Hα + [NII] emission blend

- Employ various detectability constraints for the broad component:
  - only strong features observed initially ($f_{H\alpha}$ > 0.6 for lower resolution observations, ground-based)
  - Weaker features detected at later time ($f_{H\alpha}$ > 03, for higher resolution HST-STIS observations)
- Results of simulation reflect observational findings and support idea of decade-scale variability (Constantin et al. 2015)



Future Directions

1. Implement parameter distributions that more closely match measurements from AGN surveys (instead of simply uniform)
2. Couple the parameters used in modeling the Hα broad and narrow fluxes
3. Employ a distribution of periods for the sample of objects (current model and results apply to only T = 10 years)
4. Implement a distribution for the variability amplitudes (so that surveyed/modeled AGNs are not varying in broad flux to the same degree)
5. Develop and test a model for Hα narrow line variability in conjunction with BLR variability (while matching observational data)
6. Add stellar continuum of various strength into modeled spectra to better gauge the detectability of the BLR

Based on this analysis we will be able to place new strong constraints on AGN census and thus an accurate census of SMBHs in the universe

References

Constantin, A., & Seth, A. C. 2012, Advances in Astronomy, 2012, 13
Constantin, A., Shields, J. C., Ho, L., 2015, ApJ, 814 (2), 14
Filippenko, A. V., & Sargent, W. L. W. 1985, ApJS, 57, 503
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997a, ApJS, 112, 315
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997b, ApJS, 112, 391
Peterson, B., M. 1997, An Introduction to Active Galactic Nuclei (Cambridge, UK: Cambridge University Press)
Peterson, N., M. 2001, Variability of Active Galactic Nuclei (Columbus, OH: The Ohio State University)